HIGH ENERGY NEUTRON-PROTON SCATTERING WITH SPIN-ORBIT INTERACTION.

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ABSTRACT The angular distribution and total cross sections have been calculated for high energy n−p scattering in the energy-range 83–415 Mev (laboratory system). The interaction considered is of a symmetrical type with spin-orbit and tensor force in the triplet states. Yukawa potential has been used with ranges 1.18×10^{-13} cm. and 1.60×10^{-13} cm. in the singlet and triplet states respectively. The parameters of the potential are fitted to explain the low energy scattering cross section and the properties of the deuteron. The calculated high-energy cross sections are, as usual, large The symmetrical meson theory with tensor force and spin-orbit interaction does not seem to be capable of explaining the high-energy scattering data.

1. INTRODUCTION

The theoretical investigations of high energy n − p scattering with non-central interaction have been carried out by a number of workers [Ashkin and Wu, (1948), Massey, Burhop and Hu (1948) Hsu and Hu (1948), Eisenstein and Rohrlich (1948), Burhop and Yadav (1948, 1949), Yadav (1952), Castillejo and Richardson (1949), Jastrow (1950, 1951)]. The calculated cross section is too large compared with the experimental results. More recently, Gammel and Thaler (1956), Wertheim, Hull and Saperstein (1956) and Christian, Gammel and Thaler (1957) have performed calculations with phenomenological nucleon-nucleon potential, but the results are, as usual, far from satisfactory.

In view of the present circumstances, it is interesting to see the effect of a velocity dependent force (such as a spin orbit force) in the nucleon-nucleon inter action. Case and Pais (1950) were the first to consider the spin-orbit term of the type L.S., where L is the orbital angular momentum vector and S the spin vector for the two-nucleon system. They used Born approximation to fit the 32 Mev and 350 Mev scattering data using a highly singular radial dependence of potential with L. S. term. But it has been shown by Swanson (1953) that Born approximation gives unreliable results with singular potentials even at very high energy However, the qualitative conclusion of Case and Pais is that L.S. term gives pre ference to 90° scattering (in the centre-of-mass system), which is exactly what is wanted to explain the scattering data. Also Goldfarb and Feldman (1952)

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have shown that only L. S. interaction in triplet odd states is incapable of explaining the experimental p—p scattering data.

As no exact calculations with L.S. term in the nucleon-interaction are available since the Born approximation estimate of Case and Pais (1950), the investigation of L. S. potential in high energy nucleon-nucleon scattering deserves further study. Consequently, it was considered worthwhile to undertake the exact calculations with tensor force and spin-orbit term in the triplet interaction with exchange properties given by symmetrical meson theory. Since the present work began, Chnuma and Feldman (1956) made a phase-shift analysis of the experimental cross sections at 150 Mev and their conclusion is that almost every set of acceptable phase-shifts favours the inclusion of spin-orbit potential. The existence of spin-orbit potential in nucleon-nucleon interaction is also supported by the work of Wolfenstein (1956) and also from the success of the shell model for complex nuclei.

The results obtained in the present attempt are large as usual, and possibly the spin-orbit term (along with tensor force), used with conventional potentials (spherical, Gaussian, exponential, Yukawa) is not enough to explain the scattering data. Also the symmetrical theory gives too much backward scattering ($\theta = 180°$) which is not in agreement with experiment except at very high energy $\simeq 300$ Mev. Calculations were performed in the energy range 83 to 415 Mev (lab. system).

2. THE INTERACTION POTENTIAL

(i) *Triplet states*: The interaction potential with exchange properties as given by symmetrical meson theory was chosen as it has been found to fit the experimental data better [Hsu and Hu (1949), Christian (1952)]. The potential taken is of the form

$$^3V = \frac{1}{3}\vec{\tau}_1 \cdot \vec{\tau}_2 \frac{\hbar^2}{Mr_0^2} \left\{ \frac{a}{4}(\vec{\sigma}_1 \cdot \vec{\sigma}_2 + 3) + a\gamma S_{12} + g(\vec{\sigma}_1 \cdot \vec{\sigma}_2 - 1) + a\alpha\, \mathbf{L}.\mathbf{S} \right\} v(r/r_0) \quad \ldots \quad (1)$$

where $\vec{\sigma}_1$ and $\vec{\sigma}_2$ are the spin-vector operators, τ_1, τ_2 the corresponding isotopic spin operators and $\mathbf{r}$ the relative position vector for the two particles. S_{12} is the tensor force operator and is equal to $\frac{3}{r^2}\{(\vec{\sigma}_1 \cdot \mathbf{r})(\vec{\sigma}_2 \cdot \mathbf{r})\} - \vec{\sigma}_1 \cdot \vec{\sigma}_2$, a, γ, g, α are dimensionless constants and $v(r/r_0)$ is a function that defines the radial dependence of potential of range r_0; $\mathbf{L}.\ \mathbf{S}$ is the spin-orbit force introduced in the interaction, $\mathbf{L}$ is the orbital angular momentum and S the spin vector for the two-nucleon system. Assuming the radial dependence of potential to be of Yukawa type, the potentials for triplet even and odd states are respectively

$$^3V_{even} = -\frac{\hbar^2}{Mr_0^2}\{a + a\gamma S_{12} + a\alpha \mathbf{L}\ .\ \mathbf{S}\} \frac{e^{-r/r_0}}{r/r_0} \tag{2}$$

$$^3V_{odd} = -\frac{1}{3}\,{}^3V_{even} \qquad \ldots \quad (3)$$

where the triplet range $r_0 = 1.60 \times 10^{-13}$cm.

All the constants were calculated to fit the low energy scattering and the properties of the deuteron in the usual manner (Yadav, 1952 ; Hu and Massey, 1949). The values obtained are

$a = 1.816$; $\gamma = 0.756$, $\alpha = -0.603$.

D-state admixture for the ground state of the deuteron $= 3.16\%$

(ii) *Single states* —The singlet potential is

$$^1V = -\frac{\hbar^2}{Mr_s^2}\,\vec{\tau}_1 \cdot \vec{\tau}_2\, g\,\frac{e^{-r/r_s}}{r/r_s} \qquad (4)$$

which for even and odd states become respectively

$$^1V_{even} = -\frac{\hbar^2}{Mr_s^2}\, g\,\frac{e^{-r/r_s}}{r/r_s} \qquad (5)$$

$$^1V_{odd} = +3\,{}^1V_{even} \qquad (6)$$

This is taken from the calculations of Hsu and Hu (1949) and Breit *et al.* (1952). The constants are, $r_s = 1.18 \times 10^{-13}$ cm., and $g = 1.575$ and fit the results of low energy n$-$p and p$-$p scattering correctly.

3. THEORY OF CALCULATION

(i) *Triplet states* — The phase-shifts for the coupled states $^3S_1$ and $^3D_1$ and for uncoupled states $^3P_0$, $^3P_1$ and $^3D_1$ were calculated from the exact solutions of the radial wave equations obtained by numerical integration by Gauss and Jackson method [Jeffreys and Jeffreys, 1946] The phases for higher angular momentum states, being very small, were taken into account by Born approximation. The procedure followed in brief is given below.

Introducing the potential (2) in Schroedinger's equation for the two-body system in the centre-of-mass co-ordinates, we have

$$\Delta^2\psi + \left[\frac{ME}{\hbar^2} - \frac{a}{r_0^2}(1+\gamma S_{12}+\alpha \mathbf{L.S})\,\frac{e^{-r/r_0}}{r/r_0}\right]\psi = 0 \qquad \ldots \quad (7)$$

where the eigen value of the $L.\,S.$ operator $= \frac{1}{2}\{J(J+1)-L(L+1)-S(S+1)\}$ J being the total angular momentum vector, $\mathbf{J} = \mathbf{L}+\mathbf{S}$.. Putting the value of the triplet state wave function (Hu and Massey (1949) in (7), we get after some usual manipulations

$$\left\{\frac{d^2}{dr^2}+\frac{k^2}{r_0^2}-\frac{L(L+1)}{r^2}\right\} f_{JJ_zL}=\left(\frac{M}{\hbar^2}\int\sum_{L'} F^*{}_{JJ_zL}VF_{JJL'}f_{JJ_zL'}\, d\,\Omega\right)$$

where $k^2=\frac{ME}{\hbar^2}r_0^2$, and other notations are the same as in the paper referred to above. Introducing the value of ${}^3V_{even}$, the equation for the triplet even state is

$$\left\{\frac{d^2}{dr^2}+k^2-\frac{L(L+1)}{r^2}\right\} f_{JJ_zL}=-\frac{1}{r_0^2}\sum_{L'}[a\delta_{LL'}+a\gamma< L|S_{12}|L'>$$

$$+a\alpha\,\mathbf{L}.\,\mathbf{S}\;\delta_{LL'}]\,f_{JJ_zL'}\,\frac{e^{-r/r_0}}{r/r_0} \qquad \dots \quad (9)$$

where the matrix elements $< L\,|\,S_{12}\,|\,L' > = <\overset{*}{F}_{JJ_zL}\,|\,S_{12}\,|\,F_{JJ_zL}>$

$=2$, for $J=L$, and all other matrix elements vanish. The differential equation for triplet even states for $J=L$, is

$$\left[\frac{d^2}{dx^2}+k^2-\frac{L(L+1)}{x^2}+a(1+2\gamma-\alpha)\frac{e^{-x}}{x}\right]f_{JJ_zL}=0 \qquad \dots \quad (10)$$

where $x=\frac{r}{r_0}$

And, for triplet odd states for $J=L$, the equation is the same as (10) with a replaced by $-\frac{a}{3}$.

Considering the case for $L=J-1$, $<L|S_{12}|L'>$ has the following values

$$<J-1\,|\,S_{12}\,|\,J-1> = -\frac{2(J-1)}{2J+1}.$$

$$<J-1\,|\,S_{12}\,|\,J+1> = \frac{6[J(J+1)]^{\frac{1}{2}}}{2J+1}$$

$$<J-1\,|\,S_{12}\,|\,J> = 0.$$

and the eigen value of $L.S=J-1$, for $L=J-1$. The right-hand side of (9) becomes

$$=-\frac{a}{r_0^2}\left[1+\alpha(J-1)-2\gamma-\frac{(J-1)}{2J+1}\right]\frac{e^{-x}}{x}f_{JJ_z,\,J+1}-\frac{6a}{r_0^2}\gamma\,[J(J+1)]^{\frac{1}{2}}$$

$$\times\frac{e^{-x}}{x}\,f_{JJ_z,\,J+1}$$

and the equation for triplet even states for $L=J-1$, becomes

$$\left[\frac{d^2}{dx^2}+k^2-\frac{L(L+1)}{x^2}+a\left\{1+\alpha(J-1)-2\gamma\frac{(J-1)}{2J+1}\right\}\frac{e^{-x}}{x}\right]f_{JJ_z,\,J-1}$$

$$+6a\gamma\frac{\{J(J+1)\}^{\frac{1}{2}}}{2J+1}\frac{e^{-x}}{x}f_{JJ_z,\,J+1}=0 \qquad \ldots \quad (11)$$

Replacing a by $-a/3$ in the above equation, we get the corresponding equation for triplet odd states.

Finally, for $L=J+1$, $L.\,S=-(J+2)$, and

$<L|S_{12}|L'>$ has the following values

$$<J+1\,|\,S_{12}\,|\,J+1> = -\frac{2(J+2)}{2J+1}.$$

$$<J+1\,|\,S_{12}\,|\,J> = 0.$$

$$<J+1\,|\,S_{12}\,|\,J-1> = \frac{6[J(J+1)]^{\frac{1}{2}}}{2J+1}.$$

The right-hand side of (9) is

$$=-\frac{a}{r_0^2}\left[1-\alpha(J+2)-2\gamma\frac{(J+2)}{2J+1}\right]\frac{e^{-x}}{x}\cdot f_{JJ_z,\,J+1}$$

$$-6\frac{a}{r_0^2}\gamma\frac{[J(J+1)]^{\frac{1}{2}}}{2J+1}\frac{e^{-x}}{x}\cdot f_{JJ_z,\,J-1}$$

and, we have the differential equation for even states with $L=J+1$.

$$\left[\frac{d^2}{dx^2}+k^2-\frac{L(L+1)}{x^2}+a\left\{1-\alpha(J+2)-\frac{2\gamma(J+2)}{2J+1}\right\}\frac{e^{-x}}{x}\right]f_{JJ_z,\,J+1}$$

$$+6a\gamma\frac{[J(J+1)]^{\frac{1}{2}}}{2J+1}\frac{e^{-x}}{x}f_{JJ_z,\,J-1}=0 \qquad \ldots \quad (12)$$

and similar equation for odd states with a replaced by $-a/3$.

(ii) *Singlet states* :—

In this case the equations are

$$\frac{d^2u}{dx^2}+\left[k_s^2-\frac{L(L+1)}{x^2}+g\frac{e^{-x}}{x}\right]u=0 \qquad \ldots \quad (13)$$

for even states.

and

$$\frac{d^2u}{dx^2}+\left[k_s^2-\frac{L(L+1)}{x^2}-3g\frac{e^{-x}}{x}\right]u=0 \qquad \ldots \quad (14)$$

for odd states.

where $k_s^2 = \frac{ME}{\hbar^2} r_s^2$, $x = r/r_s$, and u = wave function for the state in question; r_s = the range in singlet states $= 1.18 \times 10^{-13}$ cm.

The equations for $^3S_1+^3D_1$, $^3P_0$, $^3P_1$, and $^3D_2$ states were solved exactly, the method of obtaining the initial solution and the procedure followed are outlined by Mott and Massey (1949). Similarly for the singlet $^1S_0$, $^1P_1$ and $^1D_2$ states exact solutions were performed. The phase shifts for the above-mentioned states were calculated. In order to take the higher states into account by Born approximation, phases were also calculated for the above states by Born approximation following Ashkin and Wu (1948). The procedure for taking into account the higher angular momentum states has been given by one of us [Yadav, 1952]. The scattering cross sections were also calculated entirely by Born approximation for comparison. The method of calculating the matrix elements for scattering amplitudes in Born approximation is well known [Burhop and Yadav, 1949; Askhin and Wu, 1948] and will not be given here.

4. RESULTS

The phases are given in radians in Table I, and the angular distribution in 10^{-26} cm.^{2}/sterad. in Table II. The real and imaginary parts of the triplet coupled phases satisfied the relations given by Rarita and Schwinger (1949).

In the table, A stands for $(e^{2i\eta}-1)$, and B for $2i\delta$ where η = exact phases, and δ = phases calculated by Born approximation, m = magnetic quantum number $= 0, \pm 1$.

TABLE I

(a) Triplet coupled phases for states $^3S_1$ and $^3D_1$.

Energy in Mev.		$^3S_1$ $m = \pm 1$	$^3S_1$ $m = 0$	$^3D_1$ $m = \pm 1$	$^3D_1$ $m = 0$
83	A.	$-1.604+0.860i$	$-1.418+0.784i$	$-0.151+0.264i$	$+0.034+0.188i$
	B.	$+1.164i$	$+1.799i$	$-0.131i$	$+0.496i$
166	A.	$-1.253+1.026i$	$-1.012+0.876i$	$-0.208+0.374i$	$+0.032+0.225i$
	B.	$+1.083i$	$+1.586i$	$+0.078i$	$+0.520i$
249	A.	$-1.051+1.053i$	$-0.791+0.856i$	$-0.234+0.435i$	$+0.028+0.237i$
	B.	$+1.032i$	$+1.335i$	$+0.205i$	$+0.508i$
332	A.	$-0.916+1.047i$	$-0.649+0.818i$	$-0.245+0.470i$	$+0.022+0.240i$
	B.	$+0.993i$	$+1.194i$	$+0.290i$	$+0.491i$
415	A.	$-0.818+1.032i$	$-0.549+0.778i$	$-0.251+0.496i$	$+0.020+0.242i$
	B.	$+0.963i$	$+1.086i$	$+0.349i$	$+0.472i$

TABLE I (*contd.*)

(b). Triplet uncoupled phases

Energy in Mev.	Phases	$^3P_0$	$^3P_1$	$^3D_2$
83	η (exact)	+0.130	−0.180	+0.602
	δ (Born)	+0.069	−0.263	+0.344
166	η	+0.119	−0.224	+0.644
	δ	+0.075	−0.285	+0.448
249	η	+0.111	−0.236	+0.655
	δ	+0.075	−0.286	+0.489
332	η	+0.106	−0.241	+0.650
	δ	+0.074	−0.283	+0.509
415	η	+0.101	−0.240	+0.643
	δ	+0.073	−0.278	+0.518

(c). Singlet phases

Energy in Mev.	Phases	$^1S_0$	$^1P_1$	$^1D_2$
83	η (exact)	+0.771	−0.345	+0.314
	δ (Born)	+0.628	−0.559	+0.066
166	η	+0.665	−0.486	+0.272
	δ	+0.589	−0.669	+0.100
249	η	+0.604	−0.543	+0.263
	δ	+0.554	−0.704	+0.117
332	η	+0.563	−0.574	+0.254
	δ	+0.525	−0.716	+0.128
415	η	+0.531	−0.591	+0.248
	δ	+0.502	−0.718	+0.134

TABLE II

(a) Exact differential cross section $\sigma(\theta)$ in 10^{-26} cm.^{2} sterad. (θ = angle of scattering in the centre-of-mass system).

θ \ Energy in Mev.	83	166	249	332	415
0	3.484	3.171	3.199	3.268	3.341
15	2.794	1.738	1.419	1.362	1.267
30	2.066	1 041	0.695	0.507	0 392
60	0.861	0.349	0.201	0.134	0.098
90	0.630	0.234	0 130	0.084	0.060
120	1.067	0.471	0.276	0 184	0.128
150	4.179	2.572	1.828	1.375	1.079
165	6.684	5.656	5.421	5.205	4.960
180	7 472	6.215	5.972	5.890	5.875

(b) Born differential cross sections

θ \ Energy	83	166	249	332	415
0	3.558	3.791	3 892	3 950	3.987
15	1.295	1 274	1.275	1.250	1.204
30	0 783	0.522	0.383	0.295	0.234
60	0.303	0.120	0.067	0.043	0 031
90	0.380	0.146	0.079	0 050	0.035
120	0.973	0.450	0.265	0 177	0.113
150	3.305	2.335	1.727	1.328	1.054
165	5 344	5.376	5 354	5.218	5 001
180	6.043	6.132	6.171	6.192	6.206

(c) Total collision cross sections (in 10^{-26} cm.^{2}/sterad).

Energy in Mev.	Exact	Born	Experimental	References
83	19.34	12.99	8 3	Cook et al. (1947, 1949); Hadley et al. (1948, 1949); Dejuren (1950); Wallace (1951); Selove et al. (1953); Chin (1954); Stahl & Ramsay (1954); Chin and Powell (1957).
166	10.81	8.59	5.1	Dejuren et al. (1950, 1951); Randle et al. (1952); Taylor et al. (1951, 1953).
249	8.10	7.34	3 9	Pangher (1955); Dejuren (1950) a 269 Mev.
332	6.39	5.63	3.6	Pangher (1954, 1955) at 302 Mev. t
415	5.64	5 06	3 3	Nedzel (1953, 1954) at 410 Mev. Hartzler et al (1954) at 400 Mev.

5. DISCUSSION AND CONCLUSION

The calculated differential cross sections are much larger than the observed ones. The total cross sections obtained by Born approximation is in better agreement with experiments than the exact ones, but the former are unreliable and sometimes misleading It has been found that though the differential cross sections do not differ markedly, the partial singlet and triplet cross sections are not so. The singlet Born cross section $\sigma_s(\theta)$ is higher than the exact one, but opposite is the case for triplet cross sections $\sigma_{tr}(\theta)$ and as such when $\sigma_s(\theta)$ and $\sigma_{tr}(\theta)$ are combined to give the differential cross section $\sigma(\theta)$, an agreement is obtained. Moreover, the minimum in the cross section occurs near 60° in Born approximation, while the exact calculation gives a minimum near 90° in agreement with experiments. Also the theoretical cross section is asymmetric about 90°, $\sigma(\pi)/\sigma(0) = 2.1-1.8$ in the energy range 83—415 Mev. This asymmetry has been observed experimentally at high energy $\simeq$ 300 Mev by Pangher (1954, 1955) who found $\sigma(\pi)/\sigma(0) = 2$ nearly This is in sharp contradiction to the predictions of the Serber potential which was invoked to offer an explanation for the deep minimum and the almost symmetry about 90° near 90 Mev.

As the Yukawa potential gives the lowest cross sections (Burhop and Yadav, 1949), the L.S term used with other conventional potentials (spherical, exponential, and Gaussian) will give still larger values of cross section in disagreement with observed facts.

It seems that possibly the analysis of the high energy data in terms of static potential is doomed to a failure. We know that in the energy-range considered here, mesons are produced in nucleon-nucleon collisions and as such mesonic structure of the nucleons may play a significant role in scattering. It is probable that the meson cloud, which surrounds the nucleons and which is responsible for interaction between the nucleons, is polarized in high energy collisions. This polarization of the meson cloud round the nucleon would be expected to lead a marked change in the apparent interaction (Sachs, 1955) which may affect the scattering results considerably.

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